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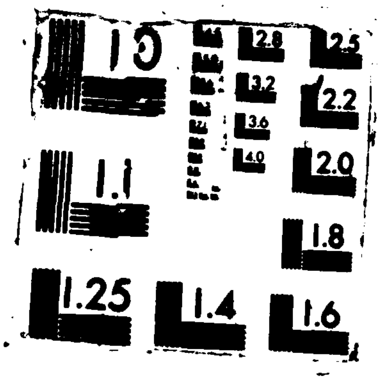

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Onset Criteria for Structure in Magnetically Confined Plasma Expansions

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Plasma Physics Division

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A set of criteria is proposed for the onset of structure caused by the unmagnetized ion Rayleigh-Taylor instability in magnetically confined plasma expansions. ~~We show that~~ R_c, the critical radius at which structure can begin to develop, is independent of the magnetic field. ~~We also show that~~ there is a critical value of laser energy that needs to be exceeded for structure to develop. These criteria are consistent with available experimental data from AMPTE and the DNA/NRL laser experiment. ~~We recommend~~ a series of laser experiments which will confirm (or refute) these criteria.

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CONTENTS

ONSET CRITERIA FOR STRUCTURE IN MAGNETICALLY CONFINED PLASMA EXPANSIONS

I. INTRODUCTION

Recent experiments have shown the rapid development of structure during the early phase of magnetically confined plasma expansions [Bernhardt et al., 1987; Ripin, 1987]. Such plasma expansions can be characterized as sub-Alfvénic, i.e., $V_{d0} < V_{Aa}$ where V_{d0} is the initial expansion velocity and V_{Aa} is the Alfvén velocity in the ambient background plasma. Under this condition the expanding plasma is 'stopped' by the magnetic field. This is in contrast to super-Alfvénic expansions where momentum coupling to the ambient plasma is primarily responsible for 'stopping' the expansion. Another feature of these expansions is that the directed ion Larmor radius ($\rho_i = V_{d0}/\Omega_i$ where Ω_i is the ion cyclotron frequency) can be comparable to or much larger than the scale sizes of interest. For instance, in the cases of AMPTE and the NRL laser experiment, $\rho_i \sim R_B >> L_n$ where R_B is the maximum radius of expansion and L_n is the scale size of the density shell. In a similar vein, one should note that the time scale (ω^{-1}) for structure development in these experiments is faster than an ion cyclotron period (Ω_i^{-1}), i.e., $\omega >> \Omega_i$. What makes this regime interesting is that it cannot be described by ideal or finite Larmor radius (FLR) MHD theory because conventional MHD theory requires $\omega << \Omega_i$ and $\rho_i << L_n$.

In order to understand the gross evolution and stability properties of magnetically confined plasma expansions, Hassam and Huba (1987a,b) recently developed a modified set of one-fluid MHD equations. These equations are valid for arbitrary values of ρ_i/L_n (or ω/Ω_i) but require $\rho_e/L_n << 1$ (or $\omega/\Omega_e << 1$) (i.e., the electrons are strongly magnetized). Linear stability analysis indicates that a fast 'unmagnetized ion' Rayleigh-Taylor instability can develop during the early phase of a magnetically confined plasma expansion when $\rho_i/L_n >> 1$ (or $\omega >> \Omega_i$). The instability is driven by the deceleration of the plasma shell which produces an effective gravitational acceleration, i.e., $dV_d/dt = - g_{eff}$, acting on the density gradient associated with the plasma shell. Moreover, the eigenmode structure suggests that the density shell should exhibit plasma 'clumping'

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instead of plasma 'rippling' (as is the case with the conventional magnetized ion Rayleigh-Taylor instability). Recent 2D MHD simulations also support this type of behavior (Huba et al., 1987). Both of these features, rapid development and density clumping, are consistent with observational evidence thereby lending support to the Hassam and Huba model.

The purpose of this paper is to develop a rather simple set of criteria for the onset of structure in magnetically confined plasma expansions. We are specifically concerned with structure generated by the unmagnetized ion Rayleigh-Taylor instability discussed in Hassam and Huba (1987a,b). We show that these criteria are consistent with available experimental data, and can be readily tested in future NRL laser experiments.

II. THEORY

A. Magnetically Confined Expansions

We first show that magnetically confined plasma expansions are sub-Alfvénic. We estimate the 'stopping' radius of a magnetically confined expansion by equating the initial kinetic energy of the plasma with the magnetic energy in a volume $(4/3)\pi R_B{}^3$ where R_B is defined as the magnetic confinement radius,

$$\frac{1}{2} M_0 V_{d0}{}^2 = \frac{B_0{}^2}{8\pi} \left(\frac{4}{3} \pi R_B{}^3\right)^{1/3} \tag{1}$$

where M_0 is the mass of the plasma, V_{d0} is the initial debris expansion velocity, and B_0 is the ambient magnetic field. From (1) we obtain

$$R_B = \left(3M_0 V_{d0}^2/B_0{}^2\right)^{1/3} \tag{2}$$

We compare this distance with the equal mass radius R_M

$$R_M = \left(3M_0/4\pi n_a m_a\right)^{1/3} \tag{3}$$

which is defined as the radius of the sphere which contains a mass of ambient plasma equal to the mass of the expanding plasma. For the expanding plasma to be confined magnetically we require $R_B < R_M$. This leads to $V_{d0} < V_{Aa}$ from (2) and (3) where $V_{Aa} = B_0/(4\pi n_a m_a)^{1/2}$ is the

Alfvén velocity in the ambient plasma. Basically, when $V_{d0} << V_{Aa}$ the expanding plasma is stopped before it sweeps up very much background plasma.

B. Magnetic Deceleration

The driving mechanism of the unmagnetized ion Rayleigh-Taylor instability is the deceleration of the expanding plasma shell. This deceleration can be interpreted as an effective gravitational acceleration, i.e., $dV_d/dt = - g_{eff}$. We estimate g_{eff} based upon conservation of energy. We write

$$\frac{1}{2} M_0 V_d^2(t) + \frac{B_0^2}{8\pi} \frac{4\pi}{3} R^3(t) = \frac{1}{2} M_0 V_{d0}^2 \tag{4}$$

where the LHS of (4) is the sum of the kinetic energy of the expanding debris and the swept-up magnetic energy at time t and position R, and the RHS is the energy at t = 0. We solve (4) for $V_d(t)$ and obtain

$$V_d(t) = \left(V_{d0}^2 - \frac{B_0^2}{3M_0} R^3 \right)^{1/2} . \tag{5}$$

We take the time derivative of (5) to obtain

$$g_{eff}(t) = - \frac{dV_d}{dt} = \frac{B_0^2}{2M_0} R^2(t) \tag{6}$$

where we have made use of the fact that $V_d = dR/dt$.

We also note that the position of the debris shell can be determined as a function of time from (5). Namely, (5) can be rewritten as

$$t = \int^R \frac{dR'}{V_d(R')} = \int^R \frac{dR'}{\left(V_{d0}^2 - \frac{B_0^2}{3M_0} R'^3 \right)^{1/2}} \tag{7}$$

Using (7) we can determine the time t when the debris shell is at a radius R.

C. Onset Criteria for Structure

The unmagnetized ion Rayleigh-Taylor instability discussed by Hassam and Huba (1987a,b) can only be excited if $\gamma_0 > \Omega_i$ where $\gamma_0 = (g_{eff}/L_n)^{1/2}$. That is, the maximum growth rate of the magnetized ion Rayleigh-Taylor instability has to be greater than the ion cyclotron frequency in order for the ions to behave as unmagnetized particles. When this occurs then the unmagnetized ion interchange mode can be excited. Making use of this fact, and the expression for g_{eff} derived above, we then arrive at the following onset criterion for structure development in magnetically confined expansions:

$$\frac{B_0^{\ 2}}{2M_0} \frac{R^2(t)}{L_n} > \Omega_i^{\ 2} \tag{8}$$

or

$$R(t) > R_c \equiv \left(2L_n M_0\right)^{1/2} \frac{eZ}{m_i c} \tag{9}$$

where Z is the charge state of the ions. Note that R_c, the critical radius for structure development, is <u>independent of the magnetic field</u>. This is because both Ω_i and γ_0 are proportional to B_0. We do not expect that structure will be observed at $R = R_c$ but that this is the radius at which structure can begin to grow. Since it will take a number of e-folding times for the structure to be observable, we anticipate that structure should be observed at $R_{obs} = \alpha R_c$ where $\alpha \approx 1.5 - 2.0$.

Another constraint on structure development is that $R_{obs} = \alpha R_c < R_B$. That is, the magnetic confinement radius must be large enough to accommodate structure development. Alternatively, if $R_{obs} = \alpha R_c > R_B$ then the maximum deceleration of the plasma shell is not fast enough for the ions to behave as unmagnetized. Thus, we also require

$$\left(\frac{3M_0 V_{d0}^{\ 2}}{B_0^{\ 2}}\right)^{1/3} > \alpha\left(2L_n M_0\right)^{1/2} \frac{e\,Z}{m_i c} \tag{10}$$

where we have used (2) and (9). With regard to the DNA/NRL laser experiment we can rewrite (10) as

$$W > W_c = \alpha^3 \frac{\left(2L_n M_0\right)^{3/2}}{6} \frac{e^3 Z^3}{m_i^3 c^3} B_0^{\,2} \tag{11}$$

where W is the laser energy, i.e., we have assumed $M_0 V_{d0}^{\,2}/2 = W$. Thus, (11) suggests that the laser energy must exceed a critical energy (W_c) in order to observe structuring of the expanding plasma.

III. APPLICATION

We now apply the criterion developed in Sec. II to the structure observed in AMPTE and the DNA/NRL laser experiment. We rewrite (9) as

$$R > R_c = 1.3 \times 10^4 \frac{Z}{\mu} \left(L_n M_0\right)^{1/2} \text{cm} \tag{12}$$

where $\mu = m_i/m_p$, m_p is the proton mass, and we have evaluated the physical constants. For AMPTE we note that $Z = 1$, $\mu = 137$, and $L_n \simeq 4.0 \times 10^6$ cm. We take $M_0 = N_0 \mu m_p$ where N_0 is the total number of ions produced. From Bernhardt et al. (1987) we take $N_0 = 7.5 \times 10^{24}$ ions so that $M_0 = 1.7 \times 10^3$ gm. Thus, for AMPTE we find that $R_c \simeq 80$ km and anticipate structure to be observed at $R_{obs} \simeq \alpha R_c \simeq 120 - 160$ km. This is consistent with observations which indicate structure is evident at $R \simeq 150$ km. For the laser experiment we take $L_n = 0.5$ cm, $M_0 = 2.0 \times 10^{-7}$ gm, $\mu = 28$, and $Z = 10$. We choose the value of Z based on the NRL HANEX simulations (Mulbrandon et al., 1987). We find that $R_c \simeq 1.5$ cm so that structure should be observed at $R_{obs} \simeq 2.2 - 3.0$ cm. This is consistent with experimental observations for both $B_0 = 1$ kG and 10 kG.

We can also rewrite (11) as

$$W > W_c = 3.3 \times 10^{11} \alpha^3 B_0^{\,2} \frac{Z^3}{\mu^3} \left(L_n M_0\right)^{3/2} \text{erg} . \tag{13}$$

For the laser experiment we note that $W_c = 16 - 38$ J for $B_0 = 10$ kG and $W_c = 0.16 - 0.38$ J for $B_0 = 1$ kG. Since $W \simeq 30$ J, (13) is marginally satisfied for $B_0 = 10$ kG and easily satisfied for $B_0 = 1$ kG. We would expect that the unmagnetized ion Rayleigh-Taylor instability would not develop if $W < W_c$.

We now present a series of plots which graphically illustrate the above criteria. We consider the following parameters which are relevant to the laser experiment: $B_0 = 10$ kG, $L_n = 0.5$ cm, $M_0 = 2.0 \times 10^{-7}$ gm, $V_{d0} = 6.0 \times 10^7$ cm/sec, $Z = 10$, and $\mu = 28$. In Fig. 1 we plot the position of the shell R (cm) versus the time t (nsec). Curve A shows the position of a 'free streaming' debris shell and is based upon $R(t) = V_{d0}t$. Curve B shows the position of a 'decelerating' debris shell and is based upon (7). The two curves are identical for $t < 20$ nsec. The maximum expansion radius in this case is $R_{max} = 2.8$ cm. In Fig. 2 we plot the effective gravitational acceleration g_{eff} (cm/sec^2) versus the time t (nsec). It is based upon (6). We note that g_{eff} increases substantially during the expansion. In Fig. 3 we plot γ_0/Ω_i versus the time t (nsec). Here, $\gamma_0 = (g_{eff}/L_n)^{1/2}$ is the growth rate of the magnetized ion Rayleigh-Taylor instability. We show the regions of stability and instability based upon the criterion $\gamma_0/\Omega_i < 1$ and $\gamma_0/\Omega_i > 1$, respectively. We point out that structure was observed to develop at $t \approx 45$ nsec in the laser experiment which is in the unstable regime (Ripin, 1987). Finally, we present a plot of R_B, R_c, and R_{obs} (cm) versus laser energy W (joules). In calculating R_{obs} we have taken $\alpha = 1.5$. For $W < 8$ J we do not expect that structure caused by the unmagnetized ion Rayleigh-Taylor instability will develop since $R_c < R_B$. However, structure may not be observed if $W < 20$ J because it may not have time to develop.

The structure criteria suggested in this paper [(12) and (13)] can be checked with a series of laser experiments. The experiments should be designed to determine the scaling of the observed structure radius with relevant physical parameters (e.g., μ, M_0, Z), and to determine if structuring stops at sufficiently small laser energies (i.e., $W < W_c$). In the former case, the scaling $R_{obs} \propto M_0^{1/2}$ would probably be the easiest to verify. Different target materials could be used to scale R_{obs} with Z/μ. In the case of aluminum we estimate $Z/\mu = 10/28$, while for carbon we expect $Z/\mu = 1/2$. Much heavier targets (e.g., gold) may yield values of $Z/\mu < 10/28$. Thus, there may be a sufficient range Z/μ to determine if R_{obs} scales linearly with Z/μ. Of course, there is uncertainty in determining Z which could hinder this analysis. On the other hand, if the scaling with $M_0^{1/2}$ is verified, lending credence to (9), then we could use the experimental measurement of R_{obs} vs. Z/μ as means to estimate Z for different target materials. With regard to checking if structure is not observed for sufficiently small laser energies, it is recommended that the

parameters $B_0 = 10$ kG and $Z/\mu = 10/28$ are used, and to reduce the laser energy to 10 J. It could then be checked if structure is observed for $W > W_c$ and not observed for $W < W_c$.

IV. DISCUSSION

We have proposed a set of criteria for the onset of structure caused by the unmagnetized ion Rayleigh-Taylor instability in magnetically confined plasma expansions. The AMPTE magnetotail barium release (Bernhardt et al., 1987) and the recent NRL laser experiments (Ripin et al., 1987) are excellent examples of such expansions. In both cases, structure was observed on time scales fast compared to the ion cyclotron period, and the unstable density shell exhibited 'clumping' as opposed to 'rippling'. Both these features are consistent with linear theory (Hassam and Huba, 1987a,b) and 2D MHD simulations (Huba et al., 1987). Furthermore, the onset criteria proposed is also consistent with the AMPTE and laser observations. Aside from predicting R_c (the critical radius at which structure can develop), we also find that R_c is independent of the magnetic field. This latter point has recently been observed in the NRL laser experiment. Finally, we have recommended a series of experiments which will help confirm (or refute) these onset criteria. Of particular interest is the scaling of R_c with M_0, and the onset of structure for $W > W_c$.

Finally, we comment that a critical parameter in determining R_{obs} is α. At this point, the values assumed for α have guided by observational data. Although R_c is independent of B_0, it may be that α is dependent on B_0 (e.g., through the growth rate) so that R_{obs} could be dependent on B_0. For example, we find that the linear growth rate of the unmagnetized Rayleigh-Taylor instability is sufficiently fast to explain the observed structure position for both AMPTE and the $B_0 = 10$ kG laser experiment. However, for the $B_0 = 1$ kG laser experiment, the growth rate of the instabilty (at the observed wavelength) is too slow to account for the structure at the observed position. We note that the growth rate is proportional to the wavenumber (k) or mode number (m) so that rapid growth of short wavelength modes is anticipated. We speculate that there may be a rapid nonlinear cascade of energy from the short wavelength modes to the long wavelength modes that are observed. We are currently investigating this hypothesis.

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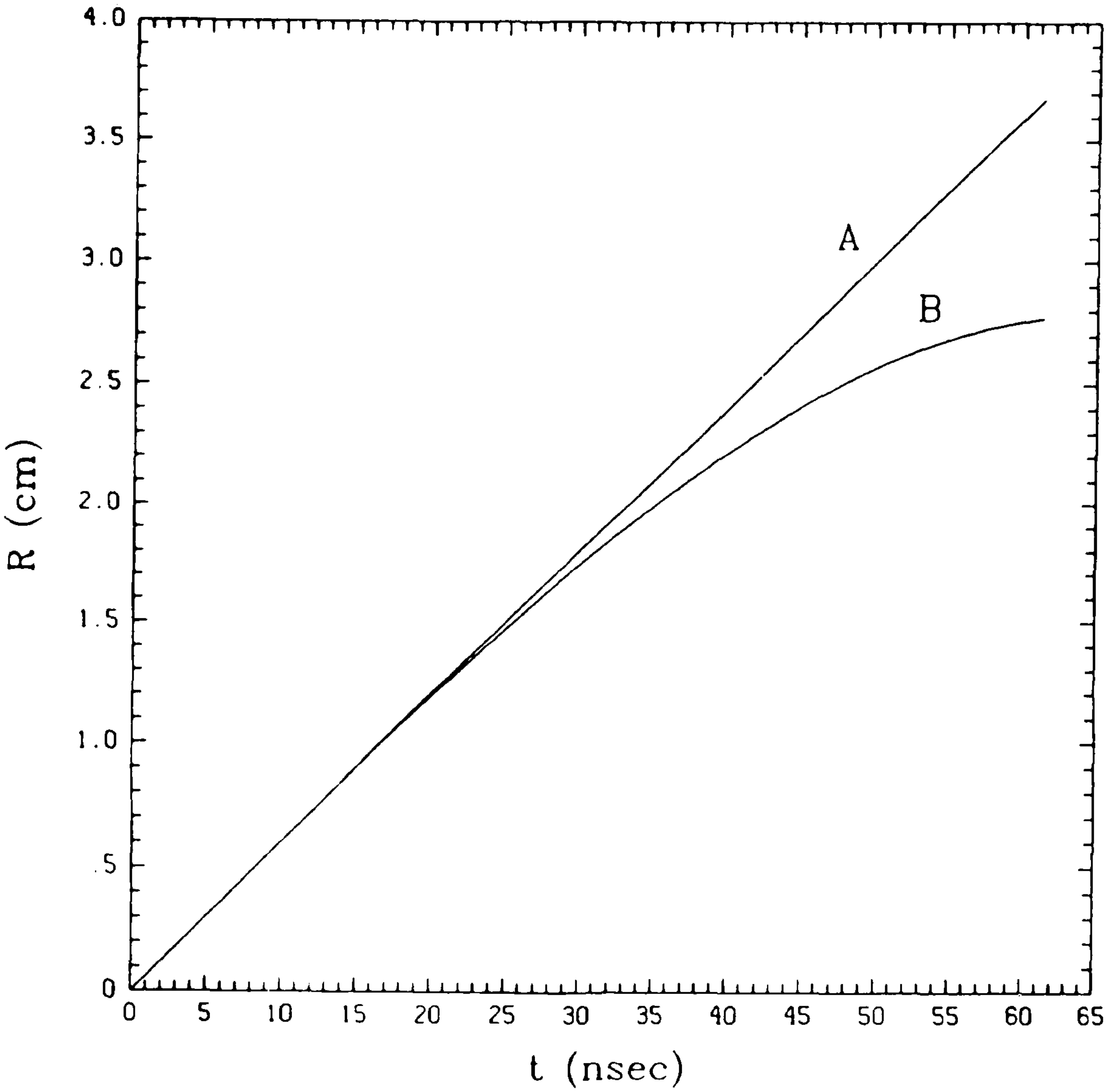

Fig. 1 — Plot of R (cm) versus time t (nsec). The parameters considered are B_0 = 10 kG, M_0 = 2.0 x 10^{-7} gm, L_n = 0.5 cm, V_{d0} = 6.0 x 10^7 cm/sec, Z = 10, and μ = 28. Curve A is for a 'free streaming' debris shell, while curve B is for a 'decelerating' debris shell and is based upon (7).

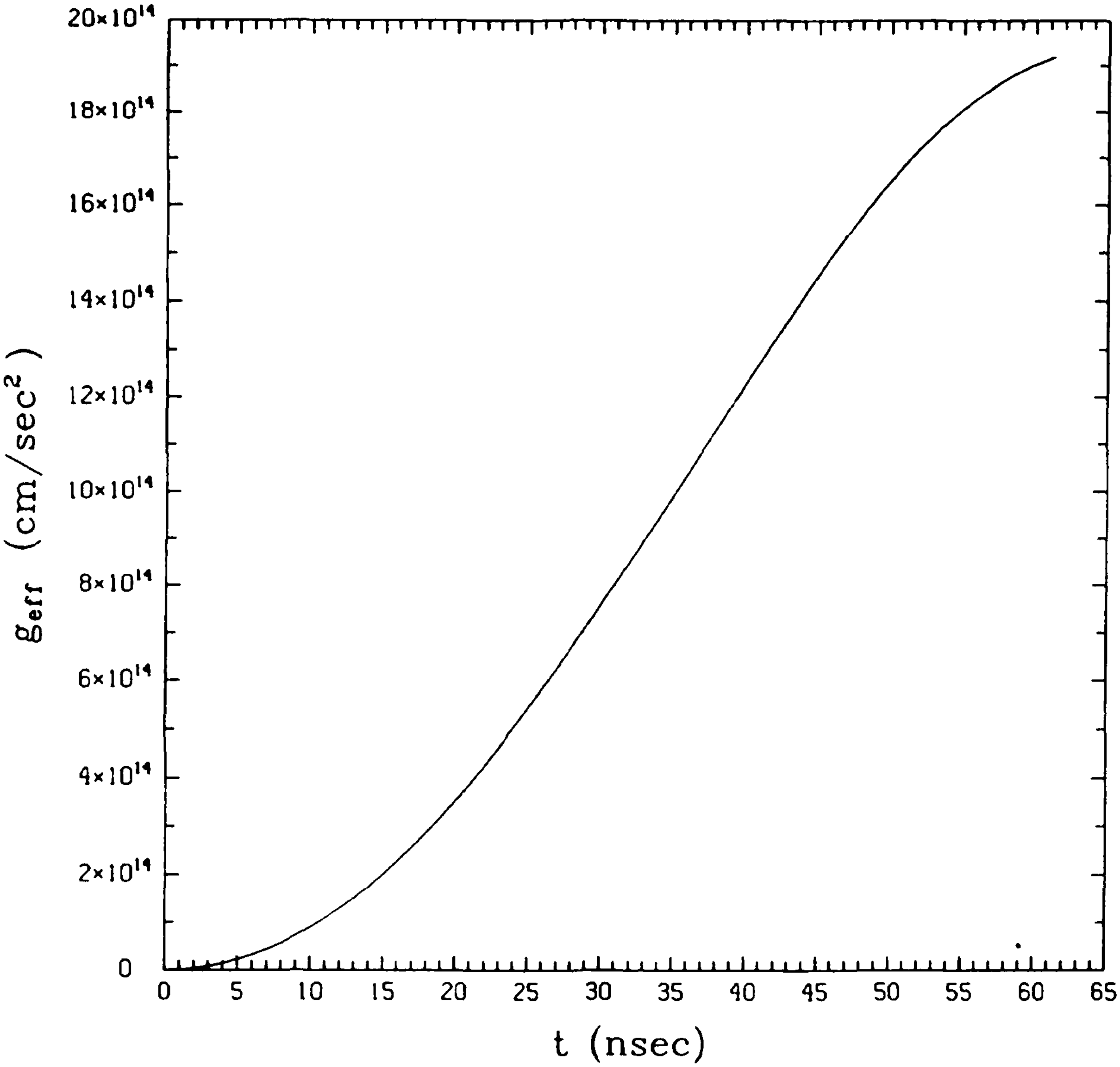

Fig. 2 — Plot of g_{eff} (cm/sec^2) versus time t (nsec). The parameters are the same as in Fig. 1.

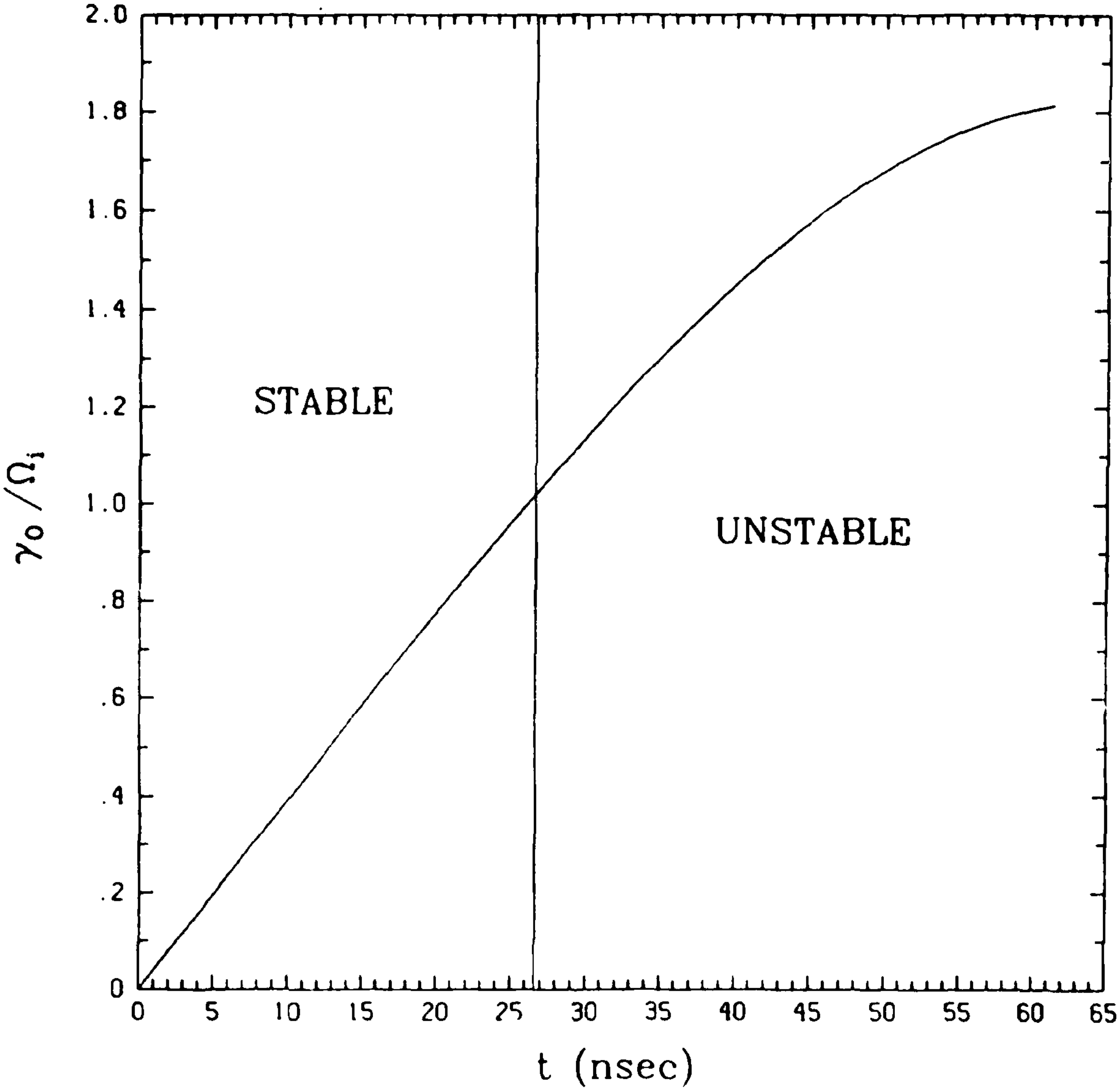

Fig. 3 — Plot of γ_0/Ω_i versus time t (nsec). The parameters are the same as in Fig. 1. The stable and unstable regions are defined by $\gamma_0/\Omega_i < 1$ and $\gamma_0/\Omega_i > 1$, respectively.

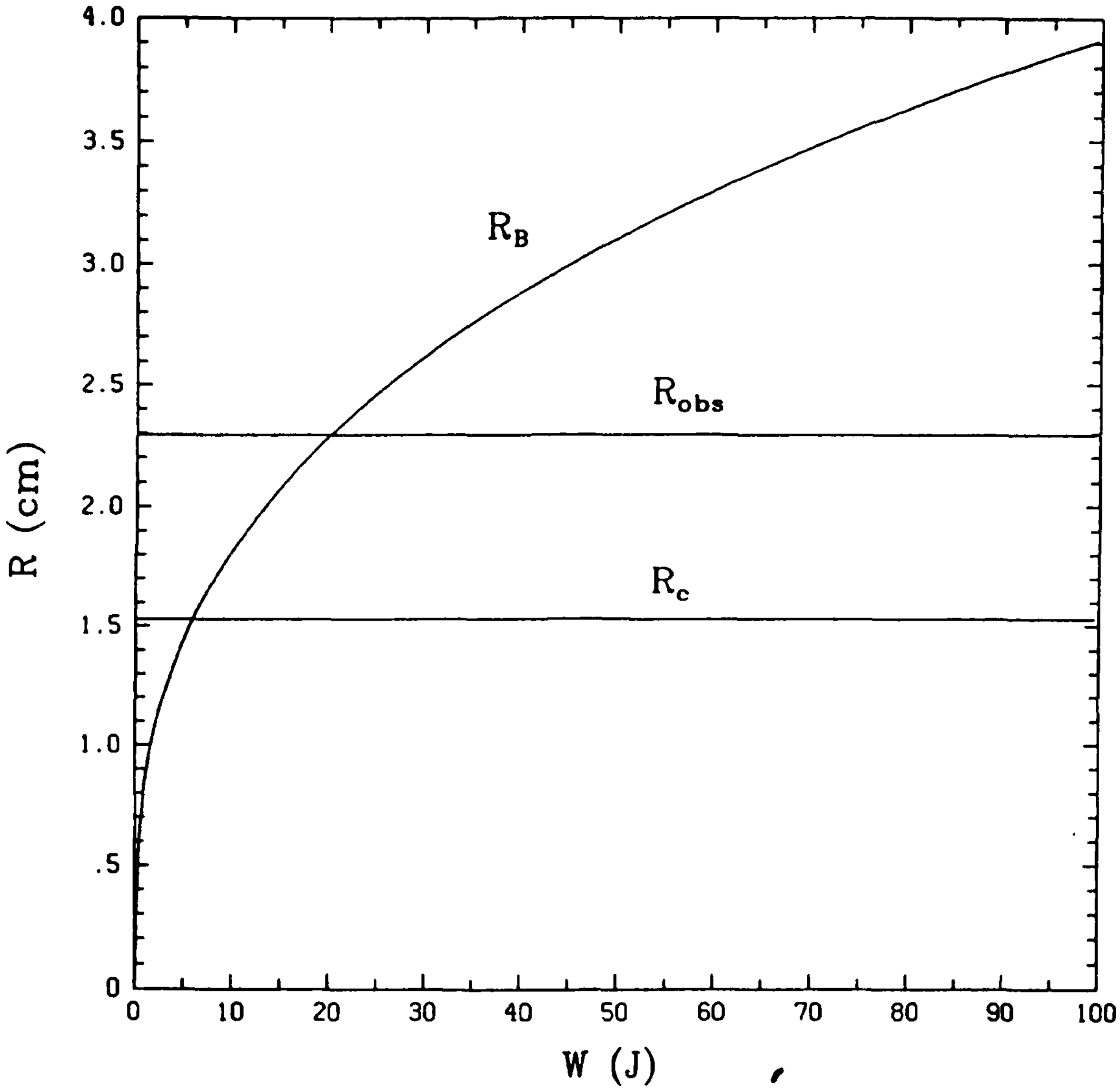

Fig. 4 — Plot of R_B, R_c, and R_{obs} (cm) versus laser energy W (joules). The parameters are the same as in Fig. 1. We assume that $W = M_0 V_{d0}^2/2$. Since R_c is taken to be constant (i.e., M_0 is a constant), V_{d0} must vary as $W^{1/2}$.

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